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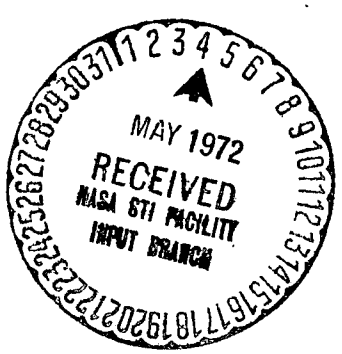


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# LUNAR DEVELOPMENT IN THE LIGHT OF MODERN DATA

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It is frequently stated that direct investigations of the moon and analysis of the samples of lunar rock and ground returned to the earth will help in an understanding of the origin and evolution of the moon, earth, and the entire solar

system. This is naturally a true statement. However, it must not be expected that the problem will be solved all at once, as a result of some unexpected discovery. We know much more about the earth than about the moon and other bodies in the solar system, and nevertheless we still continue to argue about the composition of the earth's mantle and about the nature of its dense core, not to mention the problem of the origin of our planet. The results of space explorations are bringing closer the level of our knowledge concerning the planets of the earth group, and particularly the moon, to the level of our knowledge concerning the earth. The differences in the size of bodies in this group and in their distances from the sun are responsible for the differences in the process of their formation and further development. This makes particularly valuable a comparative analysis of the collected data.

For the time being the greatest amount of new information has been obtained concerning the moon. But much of this information, particularly that which is related to the processes transpiring in the distant past or now transpiring in the deep layers of the moon, is interpreted in several ways. Like Gold, we can predict that much of the new data will be like a mirror in which each scientist will see a reflection of his own ideas.

All the factual information concerning the moon, both old and new, naturally concerns its present-day properties. The first thing which can be drawn from this information is the history of the development of these properties, that is, the history of development of the moon. Only with a clarification of the initial properties of the moon will it be possible to advance further in studying its origin.

An exceedingly important aspect of the history of lunar development is its thermal history and the magmatic differentiation of its deep layers. Until now the thermal history has been studied by mathematical computations based on cosmogonic concepts concerning the initial temperature of the moon and the surmised content of radioactive elements. The results of these computations served as a basis for drawing conclusions concerning the magmatic differentiation of deep lunar layers. There were no "boundary conditions" which would make it possible to reject some variants of the computed thermal history and to give preference to others. The new results of lunar investigations and analyses of lunar samples has already yielded important "boundary conditions" which are forcing us to introduce significant corrections into earlier concepts. Now we will endeavor to examine these corrections.

## Thermal History of the Moon

Only a few years ago it appeared that the thermal history of the moon, computed for initially cold models with a chondritic or similar radioactivity, could be consistent with the manifestations of magmatic differentiation observed on the lunar surfaceand could give an internally noncontradictory picture of its origin and development. According to the computations, based on up-to-date analyses of the content of radioactive elements in chondritic meteorites, the fusion of the lunar interior must have begun $2 \cdot 10^9$ years after formation of the moon, that is, approximately 2.5 billion years ago. Accordingly, it was postulated that the lunar seas and lava-filled craters have precisely this (or a lesser) age.

However, ages of about $3.5 \cdot 10^9$ years were obtained for the basaltic rocks from the landing sites of the Apollo 11 and Apollo 12. There is no doubt but that basalt is a product of the magmatic differentiation of the lunar interior. Accordingly, the fusion must have begun at least a billion years earlier than in recent computed models of the thermal history of the moon.

Considerably greater ages, about $4.5 \cdot 10^9$ years, close to the age of the moon itself, were obtained for the lunar ground (regolith) from the Apollo 11, Apollo 12 and Luna 16 landing sites. Since the regolith consists for the most part of fragments of contiguous rocks, as is indicated by the coincidence in the characteristics of their chemical composition (for example, both the rocks and regolith from the Mare Tranquillitatus are rich in iron and titanium), these great age differences of the rocks and regolith were met with surprise and even were doubted. However, it was later demonstrated that it is sufficient for there to be a small admixture to the regolith of the ancient component which is little reflected in its composition for the measured age of the regolith to be close to the age of this ancient impurity. The so-called continental regions, arising soon after the moon's formation, evidently belong to the ancient sectors of the lunar surface. A small quantity of matter from the continental regions is scattered on the surface of the lunar marias when impact craters are formed in the continental areas. A search for ancient rocks was included among the principal missions to be undertaken by the Apollo 14 and Apollo 15 crews and their landing sites were accordingly appropriately selected. For the time being it is still unknown to what degree this search has been crowned with success.

Meanwhile, further analyses of the samples returned

by the Apollo 11 and Apollo 12 confirmed that lunar fusion began soon after formation of the moon or even during the concluding stage in this process. Moreover, indications were found that initially there was fusion of the outer layer of the moon and its deeper layers were fused approximately a billion years later and served as a source of the dark basalts forming the lunar maria. Such a thermal history requires initially hot outer parts of the moon and initially less hot deeper layers.

The increase in initial temperature displaces the onset of fusion to an earlier time, but the present-day temperature distribution in the body of the moon almost does not change in comparison with the results of former computations. This is understandable: early fusion means an early redistribution of radioactive elements toward the surface in the course of magmatic differentiation and an early transition from heating of the moon to its cooling.

In discussing the possible sources of energy for early heating of the moon we will use as a point of departure the idea of its accumulation from a circumterrestrial swarm of bodies and particles existing during the time of accumulation of the earth itself from bodies and particles constituting a circumsolar swarm. This hypothesis of lunar origin, proposed by O. Yu. Shmidt, is the most promising. (In our opinion the continuing controversy concerning the separation of the moon from the earth is a curious episode in the history of science. The mechanical soundness of this hypothesis by G. Darwin was long ago refuted by A. M. Lyapunov (1906-1914) and E. Kartan (1924) and recent attempts to salvage the Darwinian hypothesis have not stood up under criticism. With respect to the capture hypothesis, it investigated only evolution of the lunar orbit regarded as a material point, but did not solve the problem of the origin of the moon as a cosmic body. It can be hoped that further discussion of this hypothesis will cease because all its supporters now admit that distant extrapolation of lunar orbit evolution into the past leads to a deep penetration of the moon within the Roche limit).

If it is assumed that the moon accumulated from the circumterrestrial swarm, in theory its early heating could have occurred in the following ways:

1. Heating due to the gravitational energy released during accumulation. If the gravitational energy released during formation of the moon was completely retained it could raise the mean temperature by almost 2,000°. But since it was released in the impacts of particles and bodies against the

surface, creating local heating, most of the heat was radiated into space. Only a small part of the energy could (in the form of seismic waves) penetrate quite far beneath the surface and be retained. Therefore, the real contribution of gravitational energy to the initial temperature of the moon was much less than the theoretical upper limit.

An appreciable part of the gravitational energy could be retained in the case of very rapid formation of the moon. However, in actuality there should not have been a rapid accumulation of the moon from the circumterrestrial swarm, containing the necessary supply of matter from the very beginning (it is not clear how such a swarm could arise), but its gradual accumulation, continuing to be replenished during the course of the earth's accumulation. Thus, the duration of lunar accumulation was only a little less than the duration of the earth's accumulation, that is, also $10^8$ years.

A considerable part of the gravitational energy could be retained and accordingly could create primarily a heating of the outer parts of the moon only in a case if the moon in the final stage of its accumulation had a temporarily opaque atmosphere. It is possible that such an atmosphere did exist at that time due to the degassing of the planetesimals during their impacts against the surface of the growing moon.

2. Heating by short-lived radioactive isotopes. For such heating it is necessary that the moon be formed not later than several million years after nucleosynthesis. The most promising isotope for such heating is $^{26}Al$, which has a half-life of $0.74 \cdot 10^6$ years and which cannot persist in significant quantities for more than $3\text{-}5 \cdot 10^6$ years.

Several years ago it was postulated that in addition to galactic nucleosynthesis at an early stage in the existence of the solar system an additional synthesis took place which was also associated with $^{26}Al$ formation. But even then the requirement that the time interval between nucleosynthesis and lunar formation be less than $10^7$ years was not satisfied. The moon is too large for it to be regarded as one of the bodies of the asteroid type which should be formed during the first stage in planetary accumulation.

Recently all the proposed variants of additional nucleosynthesis were rejected and the situation became much worse. It is known from the excess of $^{129}Xe$ and $^{136}Xe$ in meteorites, formed by the decay of $^{129}I$ and $^{241}Pu$ respectively, that 30-300 million years elapsed between the last galactic nucleosynthesis event in solar matter and the condensa-

tion of solid protometeoric particles which could hold radiogenic $^{129}Xe$ and $^{136}Xe$. This time interval is so great that galactic $^{26}Al$ could not be retained. One could postulate the presence of $^{26}Al$ forming in some additional nucleosynthesis. $^{26}Mg$ is a decay product of $^{26}Al$. But in meteorites and also in samples of lunar and terrestrial rocks no one has detected the slightest differences in the $^{26}Mg/^{24}Mg$ ratio. Thus, there are no indications of the presence of $^{26}Al$ in the early stages of existence of the solar system. Despite earlier hopes, the heating of $^{26}Al$ could not play an important role even in the heating of the parent bodies of meteorites, not to mention the moon, which must have been formed later.

3. Heating by electric currents induced by the intense solar wind in an early stage in existence of the solar system. The possibility of such heating is based on the premise that the young sun passed through the stage of a star of the T Tau type. In these stars corpuscular radiation is at first $10^6$-$10^7$ times more intense than the present-day solar wind and decreases by a factor of e in about $10^7$ years. Published computations showing the effectiveness of the induced heating have been based on the implicit assumption that the moon was formed virtually simultaneously with the sun.

4. Accumulation from hot particles. The idea that the moon can be a body accumulated from hot particles has been expressed by E. Anders and his associates on the basis of their analyses of lunar samples. In 1967 this same idea was expressed by E. Anders and J. Larimer relative to the accumulation of the parental bodies of meteorites. In both cases the analyses revealed the fractionation of chemical elements which can be attributed to the fact that accumulation of the moon (and the parent bodies of meteorites) occurred during the course of cooling of the solar nebula and the subsequent condensation of the more and more volatile elements and compounds. Analyses of samples returned by the Apollo 11, interpreted on the basis of these concepts, indicate that the accumulation temperature was about 600°K. This temperature is inadequate for explaining the onset of magmatic differentiation immediately after lunar formation.

However, the idea of accumulation from hot particles is based only on chemical data, and its astronomical aspect remains undeveloped. The cooling of a nebula should last a maximum of $10^5$-$10^6$ years, which is two to three orders of magnitude less than the duration of lunar accumulation.

5. Heating due to tidal deformations. The newly forming moon was probably in a state of free rotation, more rapid

than its revolution about the earth. This free rotation was soon slowed down by the dissipation of the energy of tidal deformations created by the earth's attraction. In this stage the moon should be heated by the energy of its rotation. When free rotation changed to synchronous rotation, that is, when the periods of rotation and revolution became equal, the moon continued to be heated as a result of change in the intensity of tidal deformations during its motion from apogee to perigee and back. In this process the heating arose from the energy of the earth's rotation.

The rapid withdrawal of the moon from the earth should lead to a rapid decrease in tidal energy so that for all practical purposes the heating was limited to the earliest stage in existence of the moon. A suitable selection of the inelastic characteristics of the earth and moon possibly would make it possible to obtain the necessary heating of the lunar interior.

Evidently, among the most promising of the mentioned energy sources which could lead to a high initial temperature of the moon and ensure an early onset of fusion in its interior are the gravitational energy released during accumulation and the energy of tidal deformations.

At the present time the need for changing existing models of the thermal history of the moon is based on determinations of the age of lunar samples taken only from three lunar seas. In the future there will not only be an increase in the number of various samples and the number of their age determinations, but in addition new experiments will yield new and important data for studying the thermal history of the moon.

The total content of radioactive elements in the moon can be determined from measurements of the heat flow at the lunar surface. The basaltic composition of the lunar samples returned to the earth demonstrates that the lunar materials in the interior were subjected to magmatic differentiation. In agreement with data from terrestrial geology, lunar basalts are highly enriched with radioactive elements. Accordingly, as was postulated earlier, magmatic differentiation of the lunar interior displaced the radioactive elements toward the surface and should result in a transition from lunar heating to lunar cooling. But cooling occurs so slowly that the total heat flow through the entire lunar surface is only several percent greater than the total generation of heat in its entire volume.

Heat flow measurements must be made at many points on

the lunar surface: on the maria and on the continents, in the equatorial zone and near the poles, so as to ascertain its local and regional variations and collect data for computing the total heat loss integrated along its entire surface. It can be foreseen that local and regional variations will prove to be substantial and therefore it will be necessary to make measurements at a large number of points distributed over both the visible and far hemispheres of the moon. Nevertheless, even a few measured points can improve our current inadequate knowledge concerning the release of heat in the moon.

As an additional result of these measurements it will be possible to determine the change in the thermal flow with latitude and to compare it with the computed values. According to computations, at the poles the heat flow, as a result of the lesser surface temperature, must be somewhat greater than in the equatorial zone. In addition, at the poles there should be a greater thickness of the outer solid layer and this is important for explaining the flattening of the dynamic figure of the moon.

At the present time the long-lived radioactive elements, U, Th and K, are the only heat sources in the moon. Therefore, the total heat regeneration can be converted to the content of these elements. This cannot be done with certainty: one must stipulate the values of the relative content of U + Th and K. Fortunately, this ambiguity exerts only a slight effect on estimates of the total quantity of heat released during the entire time after lunar formation and the decrease in its rate of release with time.

Information on the present-day temperature distribution in the outer layers of the moon to depths of hundreds of kilometers can be obtained by measuring variations in the magnetic and electric fields on the lunar surface and in circumlunar space. These variations can be used in judging the conductivity of the lunar interior and its increase with depth. Since conductivity is dependent on the composition and temperature of matter, these data, in combination with some hypotheses concerning the composition of the lunar interior, will give the upper limit for their present-day temperature. Unfortunately, existing theories of electromagnetic processes in space and laboratory data on the conductivity of rocks at different temperatures and pressures are still inadequate for an unambiguous interpretation of observations.

## Lunar Magmatic Differentiation

During recent decades our general ideas on magmatic

differentiation of the earth have been applied to studies of lunar magmatic differentiation, naturally, taking into account the enormous differences in pressure in the interiors of these two bodies, and therefore in their thermal histories. The pressures in the earth's lower mantle, exceeding $10^6$ atm, increase the melting temperature of silicates by approximately 3,000°, whereas the pressure of 50,000 atm existing at the center of the moon increases it only by several hundred degrees.

Several years ago computations of the thermal history of the moon led to the following picture of its magmatic differentiation: partial melting should begin almost simultaneously from a depth of about 400 km and to the center itself. Thus, the magmatic differentiation of the central region, occupying about 60% of the lunar mass, constituted the first stage in the process. Most of the long-lived radioactive elements, U, Th and K, were carried by light magma into the outer layer of the semimolten central region, toward its boundary with the outer solid layer. As a result of the continuing heating the extent of the semimolten region increased, drawing new layers into magmatic differentiation. Near the time of the maximum heating and melting, when the thickness of the outer hard layer was minimum, light magma rich in U, Th and K was impregnated into this layer and poured out onto its surface. When most of the radioactive elements was concentrated near the surface the heat which they released could easily slip off into space without heating the moon. During this stage magmatic differentiation led to a transition from heating of the moon to its cooling. The decrease in thickness of the outer solid layer was replaced by its increase. It was postulated that magmatic differentiation lasted for a limited period of time, about $10^9$ years, and accordingly volcanic activity on the lunar surface must have died out about $1.5\text{-}2 \cdot 10^9$ years ago. Since hypothetically the differentiation affected the entire lunar interior, even to its center, the subsequent epoch of lunar cooling was regarded as unsuitable for volcanic activity.

The results of direct investigations of the moon and analyses of lunar samples show, first, that the melting and magmatic differentiation of the lunar interior began $4.5 \cdot 10^9$ years ago, that is, about the time of the actual formation of the lunar body, and second, that magmatic differentiation, despite an early onset, did not end long ago but evidently continued to a relatively recent time or even is continuing at the present time.

The fact that large-scale magmatic differentiation[1] occurred soon after formation of the moon is directly related to the problem of the composition of the lunar continents. Some geologists, simply by analogy with the terrestrial continents, have assumed that the lunar continents have a granitic composition, whereas the seas have a basaltic composition. From the point of view of magmatic differentiation of the lunar interior the total replacement of the primary outer layer by the products of differentiation appeared possible and even probable. Among geologists who assumed that the lunar craters are of endogenous origin their high density on the continents caused no perplexity. However, for adherents of impact origin this constituted a problem.

Since computations of the thermal history of the moon led to the conclusion that magmatic differentiation occurred only $2 \cdot 10^9$ years after formation of the moon, the formation of the lunar continents, if they consisted of the products of magmatic differentiation, also should be related to this period. But in the case of such a late formation of the continents it would be impossible to attribute the high density of craters on their surfaces to impacts: the intensive bombardment of the moon should have ended by this time. Accordingly, the adherents to an impact origin of lunar craters regarded the continents as preserved parts of the primary outer layer subjected to intense bombardment by large crater-forming bodies during the last stage in lunar accumulation. On the other hand, it appeared strange why the blocks of solid primary lunar matter, which should be denser than the molten differentiated magma, did not sink into the latter.

Now that it has been demonstrated that the fusion and magmatic differentiation of the moon occurred at the end of its formation no difficulties arise in combining the igneous composition of the continental regions and the impact origin of the craters covering them. After the outpouring of lava its cooling and hardening could occur quite rapidly, so that with "attenuation" of lunar accumulation its surface was studded with impact craters.

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[1] Concerning the former difficulties involved in the problem of lunar differentiation and the composition of the lunar continents see B. Yu. Levin, "Four Unsolved Problems in Planetary Cosmogony," Priroda (Nature), No. 6, 1969.

The formation of the maria was a later event in the prolonged magmatic differentiation of the moon: either the impacts of large bodies, which formed circular depressions of the future maria and gave an impetus to their sinking and the subsidence of surrounding low places[1], was renewed for some unclear reason approximately $10^9$ years after lunar accumulation, or during this epoch there was a lava flooding of earlier existing depressions and low places, but then it would be necessary to explain why this flooding did not occur before.

An extremely promising theory was advanced by Wood; he postulated that the continents consist of anorthosites. About 5% anorthositic materials (real anorthosites, anorthositic gabbro, gabbroid anorthosites) were found among the small (1-5 mm)rock fragments in the Mare Tranquillitatus. At the same time, the mean composition of the ground and breccias is very similar to a mixture of 20:80 anorthosite and basalt. It is postulated that the anorthosites from the Mare Tranquillitatus constitute waste from the nearby continents. The chemical composition of the ground on the continent near Tycho Crater, measured by "Surveyor-7," is very similar to the composition of anorthosites. Anorthosites are less dense than basalts so that an anorthositic layer with a thickness of 10-20 km can explain the difference in the mean levels of the continents and maria. Finally, anorthosites have a light color, which agrees with the greater albedo of the continents. Wood asserts that the "moon, having a general composition not differing significantly from the tables of cosmic abundance of elements, other than in an incomprehensible deficit of sodium and reduced siderophyllic elements," after the crystallization fractionation on a large scale should have a core consisting of olivine, a crust consisting of anorthitic feldspar and an intermediate layer of basaltic composition. This model is extremely attractive.

Anorthosites are probably more abundant in the earth's crust than is usually assumed. Anorthosites very similar in composition to lunar anorthosites exist among ancient Archean rocks forming more than $3 \cdot 10^9$ years ago. Thus, Wood's hypothesis concerning lunar anorthosites does not necessarily require that lunar magmatic differentiation be very different from the earth's magmatic differentiation.

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[1] Some of the submerged low sectors might not have existed before but were formed as a result of subsidence of the surface caused by the great outpourings of lava.

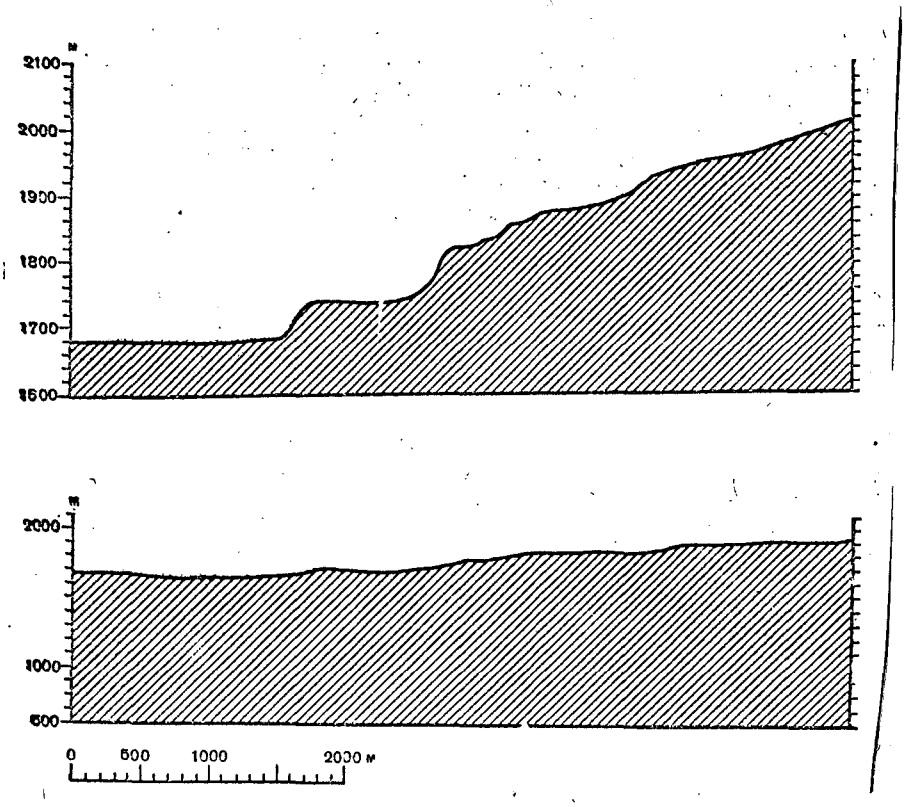


Fig. 1. Section through region of lava lakes in the northeastern part of the wall of Tycho crater. In the upper section the vertical scale has been exaggerated by a factor of five (from R. Turner, 1970).

Post-maria volcanic activity on the moon was determined on the basis of a study of large-scale photographs of Tycho, Aristarchus and Copernicus craters taken by the "Lunar Orbiters" (see figures). The appearance of volcanic processes in Tycho is particularly interesting for two reasons: first, Tycho is one of the youngest post-maria craters, and second, it is not situated on a maria, but on a continent. Lava lakes are visible on the wall, slopes and floor of Tycho (see Figures 2 and 3). Their morphological study on the basis of "Orbiter" photographs enabled R. Strom and G. Fielder (1970) to draw some important conclusions:

-- the outpourings of lava occurred even at the top of the wall and gave rise to chains of lakes situated at different levels and connected by lava flows;

-- the outpourings continued for a considerable time (possibly even long on a geological time scale);

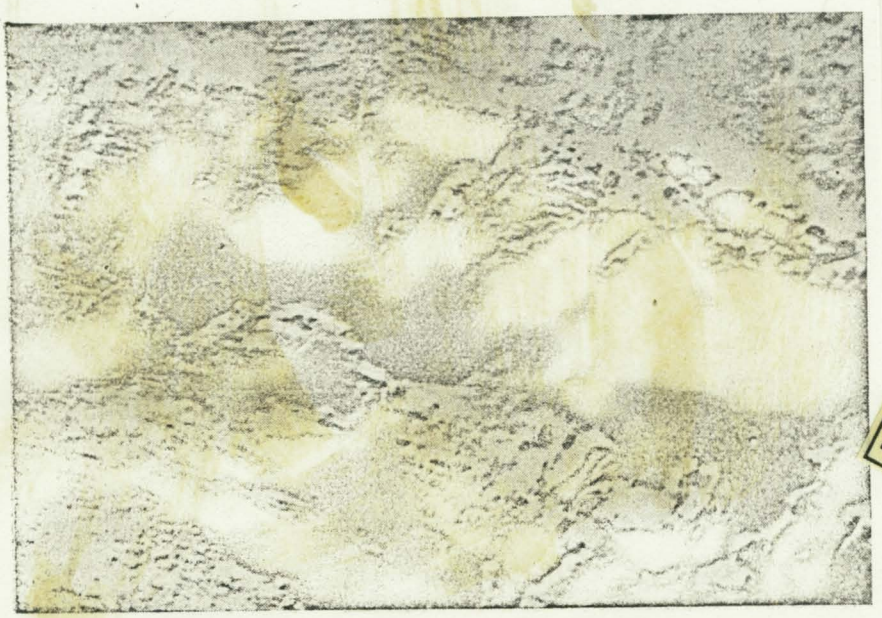

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Fig. 2. Lava lakes on the northeastern wall of Tycho Crater.

-- most of the flows consisted of extremely fluid lava, probably of basaltic composition, but some flows appear to have consisted of a more viscous lava, possibly more acidic (if this is confirmed it means that some additional differentiation can occur during such an outburst of volcanic activity, not spontaneous, but induced by crater-forming impacts);

-- flooding of the floor (at least the last, if several floodings occurred) took place later than the lava outflow on the wall;

-- the floor subsided by 25-50 m (see Fig. 3) as a result of the back flow of about three to six cubic kilometers of lava (this is indicated by the existence of a channel leading into a large lava reservoir).

Similar conclusions have been drawn concerning Aristarchus Crater (Figures 4 and 5). It is becoming increasingly clearer that the impact formation of a considerable number and possibly even all large craters was accompanied by volcanic processes of different intensity. Many aspects of these processes remain unknown. Not all researchers, for example, are agreed that the lava flooding of even the round maria was directly related to impacts and occurred quickly or soon after the impact. Some authors assume that a long period of time elapsed between formation of the maria depression and its lava flooding. This same question concerning the time interval

between impact and filling by lava or other volcanic products also remains unsolved for craters.

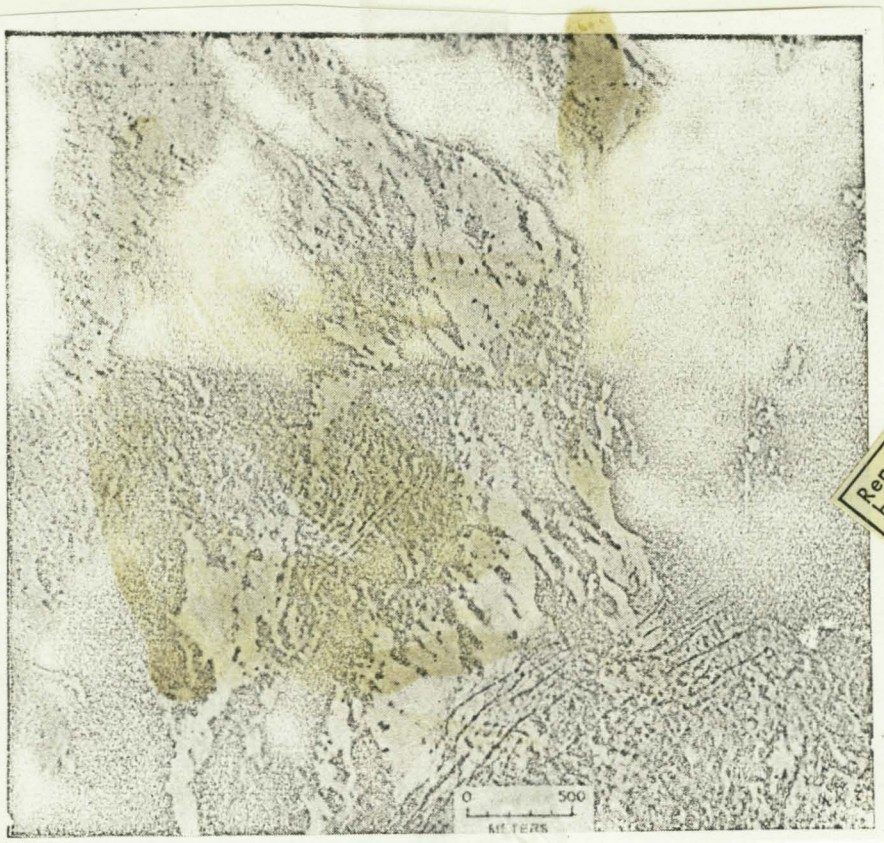


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Fig. 3. Some of the matter from lake r poured out onto the floor of Tycho Crater in the form of a short flow f. During subsequent subsidence of the crater floor cracks appeared on the surface of the congealed lava.

In the case of the maria it seems clear that the lava source is the semimolten matter present within the moon. For young craters on the continents, such as Tycho, the same deep origin of the lava seems probable, although one cannot preclude the possibility of lava formation as a result of heating caused by impact. The impacts which formed large craters should be accompanied by fracturing of the outer solid layer at a considerable depth, but how deep this cracking was propagated is subject to study. It is important to ascertain whether the lava came from beneath the outer solid layer, from the upper layer of the semimolten internal region, or whether the outer solid layer contains or in the not distant

past contained pockets of molten lava. The position (depth) of lava sources in Copernicus and Aristarchus Craters and in other post-maria craters on the maria constitutes a similar problem.

Fig. 4. Long narrow lava flow beginning at lake L (upper left corner of photograph). In the first third of its length the flow formed the channel C. The arcuate walls r formed near the exit from the channel. Next one can see the pass depressions d. It can be noted that the flow is directed at a right angle to the radial ejecta formations from Aristarchus Crater.

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Fig. 5. Southern part of the floor of Aristarchus Crater. On the boundary with the wall W there is a relatively low peripheral terrace B with a system of open cracks in the zone of maximum slope D.

An investigation of volcanic activity on the lunar surface should give an answer to another question: why is it that on the moon the volcanic activity induced by great impacts or accompanying them after some time interval evidently strongly predominates over spontaneous activity?

On the basis of computations of the thermal history of the moon the author earlier postulated that volcanic activity must have been very intense in the past, but now this epoch has already ended. However, the situation has now been changed considerably. According to W. Hartman, the age of Tycho Crater is only $2 \cdot 10^8$ years. If this age is correct, volcanic activity in Tycho must be regarded as recent.

Unfortunately, we still do not have reliable observations of present-day volcanic activity on the moon. The ob-

servation made by N. A. Kozyrev in 1959 was probably a surge of gases, possibly cold, not a true volcanic eruption. The seismicity of internal origin recently discovered on the moon may be a result of cooling and compression of the outer solid layer, unrelated to present-day volcanism. Most observations of brief lunar phenomena are essentially uncertain.

The chemical composition of the lunar samples returned to the earth, both rocks and ground (regolith), undoubtedly indicates that they constitute the products of magmatic differentiation. Only a few percent of meteoritic matter is mixed with the lunar ground and breccia. If one takes into account the considerable variations in the composition of lunar ground it can be assumed that the breccias were formed by ground compaction.

All the lunar samples were enriched by almost a factor of 100 with rare earth elements (except for europium) in comparison with chondritic meteorites. This enrichment is an order of magnitude greater than in terrestrial deep basalts. All the lunar samples (but not the deep basalts) reveal a greater negative europium anomaly: it is enriched approximately four times less than the adjacent rare earth elements. This must be associated with fractionation during the time of melt crystallization: feldspar (plagioclase), which readily incorporates europium in its structure, must be separated out from the lunar magma, transporting away about 3/4 of the europium. However, the separation out of anorthosites postulated by Wood is precisely what is required because anorthosites are rich in feldspar.

A chemical analysis of the light gray coarse-grained matter from a depth of 13-14 cm taken from the stratified core returned by the "Apollo-12" revealed that this matter, in general similar to lunar basalts, is enriched by a factor of $10^4$ with bismuth and by a factor of $10^5$ with cadmium. The investigated layer is one of the covers of ejecta thrown from different points (craters). Its enrichment with bismuth and cadmium indicates that lunar magmatic differentiation was evidently accompanied by the formation of ore deposits.

For the time being we have no firm data on whether lunar magmatic differentiation was similar to the early stages in the earth's differentiation. The differences could arise due to differences in the masses, internal pressures and thermal histories of these bodies and also due to differences (if they exist) in their total composition. However, it seems possible that present-day differences in the petrology and mineralogy of the surfaces of the moon and earth arose primarily due to

the presence of an atmosphere and hydrosphere on the earth. If this was actually the case it means that by studying the magnetic differentiation of the moon we will at the very same time study the initial stage in the earth's differentiation, which here on earth has been masked by subsequent metamorphic processes absent on the moon.

## BIBLIOGRAPHY


Vinogradov, A. P., "Preliminary Data on the Lunar Ground Returned by the 'Luna-16' Automatic Station," Priroda, No. 3, 1971.

Wood, J. A., Dickey, J. S., Marvin, U. B., Powell, B. N., "Lunar Anorthosites," Science, 167, 602, 1970.

Strom, R. G., Fielder, G., "Multiphase Eruptions Associated with the Lunar Craters Tycho and Aristarchus," Comm. Lunar Planet Lab., 8, No. 150, 1970.